2016 SCEC Proposal Report

Determining Fault Stressing Rate Uncertainties with CFM-R Based Mechanical Models of Interseismic Deformation in Southern California

Principal investigator:
Brendan Meade
Professor
Harvard University
Department of Earth & Planetary Sciences
20 Oxford St.
Cambridge, MA 02138
meade@fas.harvard.edu

(617)495-8921

Introduction

To date the SCEC effort to develop Community Stress Models (CSM) has proved vibrant, drawing together perspectives from both seismic and geodetic researchers. The RFP for 2016 SCEC proposals includes two items in the Stress and Deformation over Time section that directly address its effort:

• *Development of models of interseismic, earthquake cycle and long-term deformation, including efforts to estimate slip rates on southern CA faults, fault geometries at depth, and spatial distribution of slip or moment deficits on faults. Incorporation of rheological and geometric complexities and such models and exploration of mechanical averaging properties. Assessments of potential discrepancies of models based on geodetic, geologic, and seismic data. Development of deformation models (fault slip rates and locking depths, off-fault deformation rates) in support of earthquake rupture forecasting.*

• *Contributions to the development of a Community Stress Model (CSM), a set of spatio-temporal (4-D) representations of the stress tensor in the southern California lithosphere. In particular, we seek compilations of diverse stress constraints (e.g. from borehole or anisotropy measurements) for validation, geodynamic models that explore the coupling of side, gravity, and basal loading to observed geodetic strain-rates and co-seismically imaged stress, and studies that explore regional, well-constrained settings as test cases for larger scale models.*

The project that we propose is to extend our previous contributions to the community stress map by providing a set of sensitivities and uncertainties to stressing rate calculations derived from elastic block models constrained by interseismic GPS observations (*Loveless and Meade*, 2010). The approach and methodology are described below, and this project may be considered an additional step towards assessing the similarities and differences in stressing rate models contributed to the CSM effort.

Stressing rate estimates and uncertainties

As mentioned above, this proposal concerns uncertainties in a subclass of stressing rate models, specifically, those from geodetically constrained elastic block models. Stressing rate fields from published referenced/reference? models have been previously contributed to the Sandwell- and Becker-led CSM effort. The calculations proposed here will contribute sensitivity/uncertainty estimates for this class of models. Our rationale for this work is purely to add some metric of uncertainty to model predictions in order to inform comparisons of stressing rate models that have been assembled. The strategy is very simply to calculate stressing rates from the geodetically constrained elastic block model and then then map out sensitivities with respect to parameters including GPS station selection and fault locking depth (Figure 1). This builds on the previously published Loveless and Meade (2010) southern California block model based on the CFM-R representation of fault system geometry (Figure 2). It is not a complicated set of calculations, and it builds fromso much work we've done before that I will steer clear of repetition and pedantry. A perspective on the merits of this approach to the calculation may be summarized as:*Pros:*

• Block model derived stressing rate fields satisfies conservation of linear momentum because the Green's functions satisfy, $\boldsymbol{\nabla} \cdot \boldsymbol{\sigma} = 0$ (*Okada*, 1992; *Meade*, 2007).

• Stressing rates are analytically calculated and do not depend on the numerical differentiation of GPS velocities. This avoids the problem of seemingly high stressing rates across creeping fault segments.

• Based largely on a subset of mapped CFM-R geometry with extensions to close blocks (considered a disadvantage by some)

Cons:

- Based, largely, on subset of mapped CFM-R geometry with extensions to close blocks (considered an advantage by some)
- Stresses go singular? where Burgers vector is discontinuous. This is a standard problem in/of elasticity with discontinuous slip on non-planar fault surfaces.
- Homogenous crustal rheology, that is, no spatial variations in material properties or time-dependent stressing rates.

I can not estimate whether or not these uncertainty estimates may be sufficient to resolve apparent discrepancies between models, but I might suggest that this sort of sensitivity mapping, unsophisticated as it is, would help us to identify and localize regions of the most significant agreement. A product that could eventually come out of this line of thinking would be maps of the regions where there are significant disagreements in stressing rate estimates.

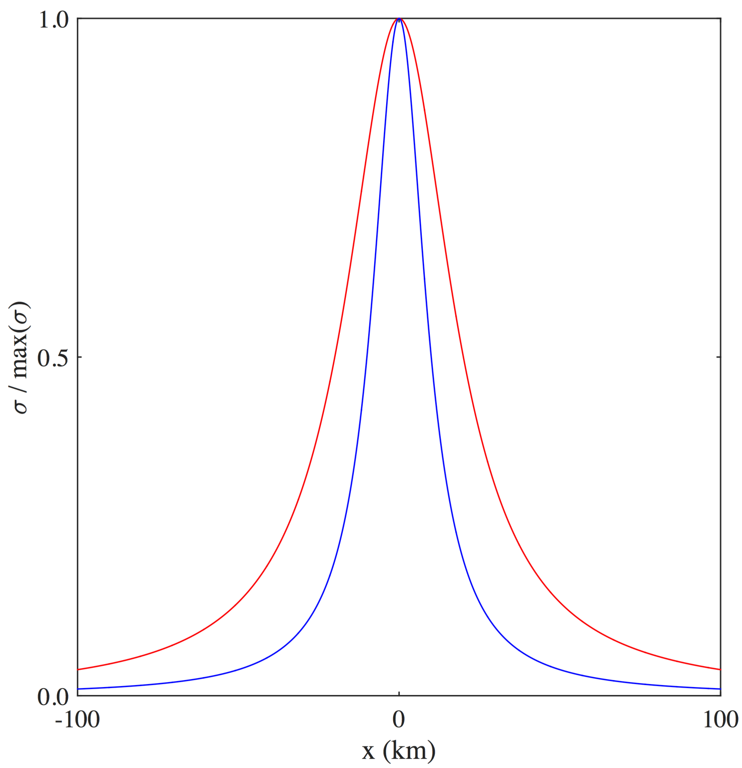

Figure 1. Two examples of normalized stressing rates as across a vertical strike-slip fault. The red line is for a locking depth of 20 km, and the blue line is for a locking depth of 10 km. While this effect is completely controlled by the ratio x/D in two-dimensions, we provide this illustration as a way of showing where our three-dimensional calculations areheaded.

Actual work

We followed the proposed workflow from the proposal pretty carefully…until we found something interesting that changed our understanding of what had to be done. The sensitvity of block model stressing rate estimate proved small with regard to GPS sub-sampling, with knockout experiments done down to 25% reduction in the number of GPS stations. This wasn't a surprise.

Our analysis of the sensitivity to fault locking depth proved a quite a different experience. What we had proposed was to simply map out the sensitivty as a function of varying locking depth (see figure 1). This seemed straightforward. However Figure 1 only looks so simple because the stresses are being evaluated at the surface far away from the bottom of the idealized dislocaiton elements with locking depths kilometers deep. As we calculated stressing rates with varying locking depths it became apparent that stressing rate uncertainty estimates where not physcaly meaningful when the observation coordinates were near any discontinuity in the Burger's vector. An example would be would be when evaluating stressing rates at the surface in the vicinity of a shallowly locked fault. In this case, the predicted stressing rates (integrated over a single year) would vastly exceed the strength of rocks. This is a problem for any calculation of this sort. As mentioned below we have found a solution to this problem through the implementation of boundary element models with linear shape functions over dislocation elements.

Summary

The central objective of this project was to calculate uncertainties in stressing rates across California using a three-dimensional geodetically constrained block model. The two primary merits of this approach are: 1) avoids numerical differentiating of GPS velocities and 2) The model is consistent with Newton's second law. The result, which some may have anticipated, was that due to the stress singularity at the edges of dislocations in Somigliana dislocation theory the uncertainty estimates of stressing rates derived from these models could not be physically interpreted except in the far-field. This suggested an alternative course forward: The development of boundary element methods that allow for linear slip transitions (shape functions) over element surfaces rather than the uniform slip shape functions assumed in classical dislocation theory. While still in development these approaches eliminate the stress singularity at dislocation edges and allow for meaningful calculations of stresses in the presence of complex fault geometry.